AD-A175 448 QUANTUM INDECISION IN LOGIC GATES(U) CORNELL UNIV ITHACA NY R L LIBOFF 25 SEP 86 ARO-20850 1-EL DAAG29-84-K-0093 1/1

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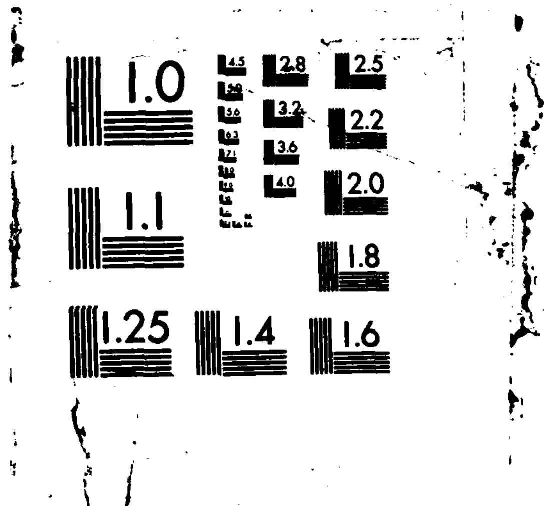

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER ARO 20850.1-EL	2. GOVT ACCESSION NO. N/A	3. RECIPIENT'S CATALOG NUMBER N/A
4. TITLE (and Subtitle) Quantum Indecision in Logic Gates		5. TYPE OF REPORT & PERIOD COVERED Technical
		6. PERFORMING ORG. REPORT NUMBER
AUTHOR(s) Richard L. Liboff		8. CONTRACT OR GRANT NUMBER(s) DAAG 29-84-K-0093
PERFORMING ORGANIZATION NAME AND ADDRESS Cornell University Ithaca, NY 14853		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
CONTROLLING OFFICE NAME AND ADDRESS U. S. Army Research Office Post Office Box 12211 Research Triangle Park, NC 27709		12. REPORT DATE September 25, 1986 13. NUMBER OF PAGES 5
MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

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19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Micro devices, Quantum indecision, Uncertainty relation, Drude approximation, Logic gate

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

(see reverse side)

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20. Abstract

Working in the Drude approximation, the following relation is obtained for relative quantum uncertainty for current flow in micro devices,

$$\frac{\Delta J}{J} \geq \frac{1}{\bar{m}^*} \frac{\lambda\!\!\!^{-}_C}{2a} \frac{c}{v}$$

In this relation, $\lambda\!\!\!^{-}_C$ is the Compton wavelength, $\bar{m}^*$ is effective charge-carrier mass divided by electron mass, v is drift velocity, c is the speed of light and a is the channel length of the conduction domain of the device. With $v \leq c$ and at fixed $\bar{m}^*$, we see that for sufficiently small values of a, the reliability of a micro logic gate is impaired due to quantum uncertainty. Application to GaAs and InP, at present-day values of maximum charge-carrier drift velocities, reveals critical scale lengths $\approx 10^{-3}$ µm.

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Introduction and Analysis

Logic gates in very large-scale integrated circuits typically employ standard variations of field-effect transistors (FET).[1,2] In micro circuits, dimensions of such devices are of the order of 1 μm. Current technology seeks to further reduce the scale-length of micro-computer networks.[3] Thus, the present work examines limitations imposed on the reliability of such logic gates due to quantum uncertainty which enters in the limit of small dimensions.[4,5]

The uncertainty relation for momentum p and displacement x is given by

$$\Delta p \Delta x \geq \frac{\hbar}{2} \tag{1}$$

Uncertainty in momentum, say, is written for the mean-square displacement from the mean,

$$(\Delta p)^2 \equiv \langle(\langle p\rangle - p)^2\rangle \tag{2}$$

With m^* denoting effective mass and v written for drift velocity we write

$$p = m^* v$$

Substitution into (1) gives

$$\Delta v \geq \frac{\hbar}{2m^* a} \tag{3}$$

where a is written for the channel length of the FET. Working in the Drude approximation,[6] we write

$$J = env \tag{4}$$

for current density, where n is charge-carrier number density and e is electronic charge. The preceding relation permits (3) to be written

$$\Delta J \geq \frac{en\hbar}{2m^{*}a} \tag{5}$$

Dividing through by current density gives

$$\frac{\Delta J}{J} \geq \frac{1}{\bar{m}^{*}} \quad \frac{\lambda_C}{2a} \quad \frac{c}{v} \tag{6}$$

where

$$\lambda_C = \frac{\hbar}{m_e c} = 3.86 \times 10^{-11} \text{ cm},$$

is the Compton wavelength, m_e is electron mass, $\bar{m}^{*}$ is the dimensionless effective mass,

$$\bar{m}^{*} \equiv \frac{m^{*}}{m_e} \quad ,$$

and c is the speed of light.

The expression (6) indicates that current resolution is maintained providing the scale-length a is sufficiently large and drift velocity v is as large as feasible.

For n-type GaAs and InP, $\bar{m}^{*} \simeq 0.07$.[7,8] Recently measured[9,10] upper limits of v indicate $v \simeq 4 \times 10^{7}$ cm/s. Substituting these values in (6) gives

$$\frac{\Delta J}{J} \geq \frac{2.14 \times 10^{-7}}{a} \tag{7}$$

Conclusions

Assuming that current resolution is lost at $\Delta J/J \gtrsim 1/2$, with (7) we find that such will be the case for scale lengths $a \leq 4 \times 10^{-7}$ cm = 4×10^{-3} μm. Repeating the calculation for p-type GaAs and InP ($\overline{m}^{*} \simeq 0.5$), gives the limiting channel length. $a \simeq 6 \times 10^{-4}$ μm.

We have applied the quantum mechanical uncertainty relation for coordinate and momentum to obtain a relation for quantum uncertainty of current flow in micro devices. It is argued that such uncertainty, when present, would destroy the reliability of input-output relations in micro-logic gates, thereby placing a lower bound on the dimensions of such devices.

Acknowledgements

Fruitful discussions with my colleagues Steve Wojtczuk, Greg Schenter and Brian Jones are gratefully acknowledged. This research was supported in part by contract DAAG 29-84-K-0093 with the Army Research Office.

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